Adding science to intuition: application of remote sensing and ecosystem modelling to vineyard management

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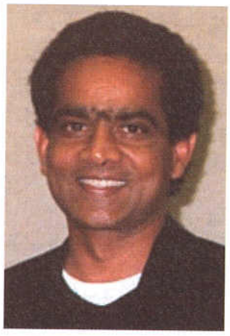

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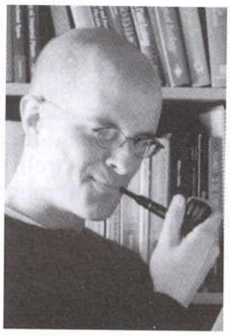

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Introduction

Proper site selection has, historically, been one of the most important aspects of fine wine production. Decades, in some cases, and centuries of experience with climate-topography-soil combinations allowed vintners around the world to identify areas that are most suitable for a given varietal. Recent research and technology have shortened the site selection process considerably. At the same time, wine production has evolved from one stemming 'out of passion' to a production management system. Large capital investments in viticulture now dictate that maximum potential of the entire vineyard be exploited, paying proper attention to marginal areas. A number of high-tech tools are available to the vineyard manager that compliment his/her intuition and knowledge in identifying and managing these marginal areas. In this paper, we discuss our experiences of applying some of these tools to vineyard management in Napa Valley, California. First, we discuss the role of remote sensing in identifying problem areas in the vineyard, and then introduce simulation modeling that may help in finding proper solutions.

Remote sensing

An aerial view of a vineyard often gives a better perspective of the prevailing conditions. This perspective, when translated to quantitative information, allows for better management prescriptions. Remote sensing, observing an object from a distance, has graduated from aerial photography to highly-sophisticated imaging sensors. These sensors can collect information at multiple wavelengths of the solar spectrum, and at spatial resolutions as fine as half a metre. Much of the remotely-sensed data used in precision agriculture are collected in the red (RED, chlorophyll absorption) and near-infrared (NIR, internal leaf scattering) wavelength bands. Various combinations of the two bands, called spectral vegetation indices, have been shown to be highly sensitive to vegetation cover and density. For example, a widely used index called the Normalised Difference Vegetation Index (NDVI), computed as (NIR-RED)/(NIR+RED), has been shown to be a useful measure of vine health and maturity (Johnson *et al.*, 1996).

Leaf Area Index (LAI, m^2/m^2)

The area of leaves per unit ground area, referred to as LAI, is an expression of the photosynthetic potential of underlying vegetation in response to a combination of climate, soils and management practices. Since LAI is a key variable controlling the water loss, photosynthesis and radiation penetration through the canopy, the ability to estimate and map LAI across vineyards would be valuable in various management decisions relating to pruning, irrigation and regulating crop loads. Over the past few years, vegetation indices have been used to delineate spatial differences in canopy conditions as a result of pest infestation and/or resource availability (Lobitz *et al.*, 1997). Similarly, vegetation indices have also been used to segment the vineyards into uniform zones of canopy vigour (Johnson *et al.*, 1996). Such segmentation was found to be helpful in maximising the production of quality wines. While the qualitative use of remote sensing is indicative of its underlying potential, we must strive to extract quantitative information to exploit its full potential. Quantitative measures such as LAI allow us to compare the data from one year to the next or from one vineyard to the next. LAI is also used as a key variable in various agronomic and ecological models for estimating canopy processes such as evapo-transpiration and photosynthesis (White *et al.*, 2000) A number of methods are available to measure LAI in the field. They include destructive methods (leaf removal, shoot length, pruning weights) and non-destructive methods based on light interception. If a relationship can be established between remote sensing data and field-measured LAI, spatial maps of LAI can be created without much effort.

With the goal of quantifying the relationship between LAI and NDVI, we chose 20 plots in Robert Mondavi vineyards, Napa Valley, California, where LAI was measured/estimated using a number of techniques (Grantz and Williams, 1993). Remotely-sensed data, acquired from an aircraft-based imaging sensor, were used to compute NDVI for each $2m^2$ area. A strong linear relationship was observed between NDVI and field-estimated LAI (Figure 1). Though theory suggests that the NDVI-LAI relation becomes asymptotic at high canopy LAIs (Myneni *et al.*, 1997), LAI of vineyards tends to

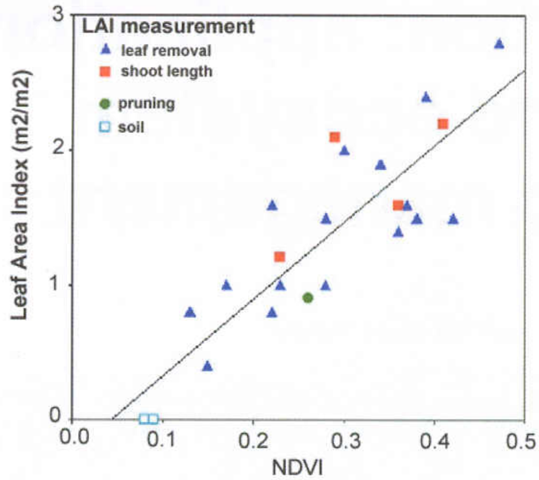

Fig 1. Observed relationship between vegetation index estimated from aircraft-based imagery and field-measured LAI over a variety of spacing and trellising systems.

be in the linear range of the NDVI-LAI relationship (<3 LAI). Interestingly, the NDVI-LAI relationship does not seem to be sensitive to the trellising types as the field-measured LAIs-represent a wide range of spacings and trellising types. A number of other factors, such as sensor calibration, soil colour, soil moisture, sun angle and viewing geometry, do influence the NDVI-LAI relationship (Myneni *et al.*, 1997). Therefore, one must pay attention to these factors when imagery from multiple dates are used.

Mapping LAI

We applied the NDVI-LAI relationship shown in Figure 1 to the entire scene shown in Figure 2 estimating LAI for each $2m^2$ area. LAI of vineyards ranged from 0.2 (in newly-planted blocks) to over 2.0 (in mature vineyards). The cost of producing such a map is less than one dollar per acre in California. Therefore, LAI maps are a cost-effective way of making decisions regarding pruning, irrigation and managing crop loads. On closer examination of the LAI map, one can see significant variations in LAI within a single block. Information on such spatial heterogeneity, caused by differences in resource availability or pest/disease infestations, can be used in two different ways. In the short run, the blocks may be divided into uniform zones that can be managed differently for fertiliser application, irrigation, and time of harvesting etc. In the long run, such information is useful in planning the vineyard: variety, spacing and trellising type. Once the vineyard is planted with the knowledge of underlying spatial heterogeneity, year-to-year management becomes more efficient and cost effective.

Fig. 2. Map of LAI for every $2m^2$ area generated using the relationship from Figure 1 over the entire imagery of Tokalon area of Napa Valley, California. An aerial view such as this map provides valuable information on the spatial heterogeneity that exists even in blocks that are managed as single entities.

Ecosystem modeling

While remote sensing is useful for detecting the spatial and temporal variations in canopy conditions, it can not explain the nderlying causes for a given canopy condition. Here we need ools that explore the complex interactions among climate, oil, vegetation and management practices. Ecosystem models re designed to combine daily weather, soil physio-chemical roperties, and vegetation physiological responses to explain he differences in vegetation stress, canopy growth and roductivity. Such models are available for almost all gricultural crops. Our model is an adaptation of a generic cosystem model, BIOME-BGC (White *et al.,* 2000b), ustomised for grape canopies. Given daily weather conditions temperature, wind, humidity, rainfall and radiation) and LAI, he model was able to reproduce measured soil moisture and egetation stress. Plant moisture status is actively managed in ineyards through pruning and irrigation. The model is also apable of estimating photosynthesis and respiration, which re useful for estimating potential productivity of vineyards. Estimates of photosynthesis-respiration balance can be used to alculate optimum crop loads, by choosing proper leaf-area-to ruit ratio. Once the models are calibrated with field bservations, they can be used in a number of ways to explore arious management options both in the site selection process s well as growing season vineyard operations.

An example of how models can be useful in vineyard nanagement is shown in Figure 3, where the amount of rrigation required to maintain a given level of vegetation tress is simulated at different LAIs. To run the model, we used laily climate data during 1999 at Napa Valley, and assumed he soils to be of sandy-loam with a depth of 120cm. As LAI ncreases, under same soil and climatic conditions, the vines equire more water on a daily basis with irrigation starting arlier in the growing season. A sensitivity analysis of the nodel using various combinations of soil-climate-LAI conditions can provide valuable information for vineyard stablishment. Models can also be used operationally to estimate irrigation requirements on a daily basis. Since weather conditions play a dominant role in irrigation equirements, the model can be set up to run on a daily basis with weather data collected in/around the vineyard. Efforts are inder way to implement the model spatially, combining the emotely-sensed LAI maps, soil texture and depth, and interpolated weather conditions (Ford *et al.,* 1993). Spatial estimates of soil moisture and evapo-transpiration can then be ised to assess where and how much water needs to be applied.

Conclusions

Advances in remote sensing technology and simulation nodeling can aid vintners in vineyard establishment as well as growing season operations. The ability to estimate and map LAI across vineyards from remote sensing at regular intervals during the growing season has not yet been fully exploited. Combining simulation models with remotely-sensed data and other ancillary information can lead to better management decisions (pruning, irrigation and crop loads), and help vineyard managers maximise the potential productivity.

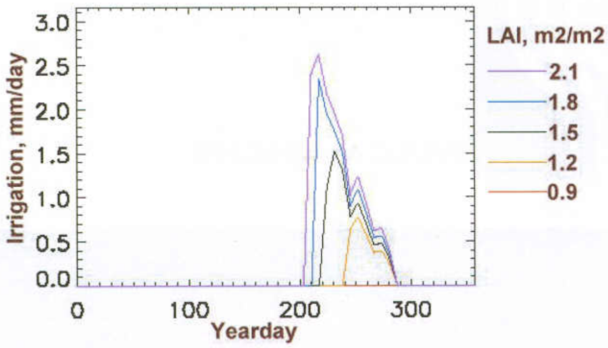

Fig. 3. Model simulations of the amount of water required to maintain vineyards with different LAIs at a given level of water stress. By introducing variations in climate and soils, one can quickly gather knowledge about the management practices that best serve a particular situation.

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